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ON RADIO EMISSION AND DIFFERENCES IN THE UPPER MANTLE OF "MARIA" AND "CONTINENTAL" REGIONS OF THE MOON

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ABSTRACT

A method is expounded for relative measurements of brightness contrasts of radio emission from various regions of the lunar disk by means of radiotelescopes of high resolution. Presented here are the results of measurements of "maria" and continental" regions' emission contrasts, in the 8 mm wave, completed with a PT-22 radiolelescope of the Institute of Physics of the USSR Academy of Sciences. These measurements point to a comparatively small difference in the brightness temperature, that is 1.5 ± 0.5% as an average for a lunation. The amplitude of contrast periodical variations does not exceed 3 percent. A conclusion is derived on the closeness of characteristics for the regions compared. The excess of night temperature of the "maria" surface in the Mare Serenitatis region, as compared with the corresponding temperature of continental surface in the Sacrobosco region, is $\sim 8^{\circ}$. This is evidence of difference in the parameter $\gamma = (k\rho c)^{-1/2}$ of these regions' material as being ~ 25 percent.

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1.- SETTING UP THE PROBLEM.-

The creation of radiotelescopes of high resolving power, to which belongs the radiotelescope PT-22 of the Institute of Physics of the USSR Academy of Sciences [1], allows in particular the investigation

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* O RADIOIZLUCHENII I RAZLICHIYAKH VERKHNEGO POKROVA "MORSKIKH" I "MATERIKOVYKH" OBLASTEY LUNY.

of the two-dimensional distribution if radiobrightness along the lunar disk. The first stage of such kind of investigations, carried out on the above-mentioned radiotelescope, provided "radioimages" of the Moon in the 8 mm wavelength [2] and in certain waves of the centimeter band. [3, 4].

These investigations have allowed to reliably establish the presence of latitude distribution of brightness temperature, conditioned by the decrease toward the poles of brightness temperature caused by solar radiation and to set up a law of such decrease. Analysis of radial distribution of brightness temperature on the lunar disk allowed the estimate of the lunar mantle's dielectric constant, found to be close to 1.5. Investigated also in a series of wavelengths was the variation of brightness temperature of the central part of the lunar disk as a function of change of Moon's phases [5], which provided new proofs of the validity of the one-layer model of its mantle.

The next stage consisted in investigations having for object to clarify the question to what extent the separate regions on the Moon differ by their physical properties and chemical or mineralogical composition. In order to resolve this question it is necessary to measure the intensity of radio emission of comparable regions with the help of a radiotelescope of sufficient resolution. With a sharp radiation pattern of $\sim 2'$ width there may be only question of comparing the regions on the lunar surface with a $\sim$200 km diameter, that is, consisting of separate "maria" and "continents". It should be noted in this connection, that the results of observations, conducted with diagrams of $5 \div 7$ angular minutes [6], related to the radio emission of separate details on the lunar disk, including even lunar craters, must be approached with great carefulness.

What kind of information can be obtained from observation of radio emission of separate regions of the lunar disk?

As is well known (see for example, [7]), $T_R(\varphi, \psi, t)$ — the mean brightness temperature of a small region with coordinates φ, ψ at the moment of time t, is expressed in the following fashion:

$$T_R(\varphi, \psi, t) = T_0 + T_1 \cos(\Omega t - \varphi - \xi), \qquad (1)$$

where $T_0(\varphi, \psi) = [1 - R(\varphi, \psi)][T_N - \frac{a_0}{2}(T_\Pi - T_N)\eta(\psi)]$ is the constant component of of brightness temperature;

$$T_1(\varphi, \psi) = [1 - R(\varphi, \psi)] \times a_1(T_\text{п} - T_\text{н})\eta(\psi) / \sqrt{1 + 2\delta \cos r' + 2\delta^2 \cos^2 r'}$$

is the amplitude of the first harmonic of brightness temperature's variable component. Here $T_\text{п}$ and $T_\text{н}$ are respectively the surface temperatures at lunar midday and midnight, $R(\varphi, \psi)$ is the radiowave reflection factor, determined in the general case by the dielectric constant ε and the degree of roughness of the surface of the emitting layer, $\delta = l_e / l_T$ is the ratio of the penetration depth of an electromagnetic with a given length, dependent upon the electrical properties of the material, to the penetration depth of the thermal wave, dependent upon the thermal parameters of the material. $\xi = \operatorname{arc\,tg} [\delta \cos r' / (1 + \delta \cos r')]$ is the lag of the first harmonic of brightness temperature relative to illuminance phase of the point considered $\Phi_0 = \Omega t - \varphi$; r' is the angle between the direction of the visual ray and the normal to the surface at observation point, with, at the same time $\cos r' = \sqrt{(\varepsilon - 1 + \cos^2 \varphi \cos^2 \psi)} / \varepsilon$.

The distinction between the properties of two regions, for example, the "maria" and the "continental" must be generally speaking, manifest in the difference in brightness temperatures $T_\text{п}$, and $T_\text{н}$. on account of several causes.

First of all the temperatures at the surface of the Moon at local lunar midday and midnight may, generally speaking, result different in various regions, depending upon the magnitudes of optical albedoes (degree of blackness). in the visible and infrared portions of the spectrum, which leads to differences in the solar radiation absorbed by the surface and in the cooling rate of the surface as a consequence of outward, space-bound radiation *.

Measurements conducted in the infrared band by M. N. Markov and V. L. Khokhlova [8], while evidence of excess of brightness temperature of "maria" regions over "continental", point at the same time to the smallness of the emitting capability or albedo difference of "maria" and "continents" in the $8 - 13\mu$ band [13]. As was shown by the recent

The temperatures, settling at midday and midnight on Moon's surface, depend also on the intensity of heat extraction at the expense of material's conductance in depth.

* For simplification we admit that heat transfer is absent along the surface.

calculations by Krotikov and Shchuko [9], the variation of the parameter $\gamma = (k\rho c)^{-1/2}$*, determining the heat balance, rxerts practically effect only on the night temperature of Moon's surface T_{H}. The day temperature T_{Γ} is nearly independent from γ.

Further, brightness radiotemperatures of comparable regions can differ because of differences in the dielectric constant and the degree of roughness. Finally, the difference in the values of amplitude and phase of the variable component of brightness temperature may be caused, besides the indicated causes, by the difference in electric and thermal parameters of the emitting layer in comparable regions, defining the value of the parameter δ.

The low value of the effective dielectric constant, which was measured by various methods during investigations of Moon's natural radio emission, and the radar investigations in the microwave band, completed recently [10], provide the basis to assume, that the emitting capability of various areas departs very little from average.

Therefore, if measurements had revealed discrepancies in the brightness temperature of comparable regions, this should be evidence in the first place, of the difference of night temperature on the surface and of of differences in parameters δ of the upper mantle of these regions, which in its turn would speak of difference of its material.

2. - RADIO EMISSION OF SEPARATE REGIONS AND CHARACTERISTICS OF THEIR MATERIAL

Measurements of radio emission of separate regions may provide the greatest information on the material of lunar mantle in the case, when these measurements have a character of absolute measurements, as a result of which one may obtain with great precision the values of brightness temperatures of the corresponding regions as a function of phase. However, as is well known (see, for example, [11]), such measurements with the help of sharply directed antennas are rather complicated. We shall show, that utilizing the presently known data on the mean parameters of the Moon and effecting the relative measurements of antenna temperatures

* Here k is the conductance, ρ is the density and c — the heat capacity of the material.

of comparable regions, on may obtain , at known reasonable assumptions, a sufficiently reliable information on the variety of properties of these regions' material.

Let $T_{H_1}(\varphi_1, \psi_1, t)$ and $T_{H_2}(\varphi_2, \psi_2, t)$ be the brightness temperatures of two regions of the lunar disk, averaged by the main lobe of a sharply-oriented or high-directional (pencil beam) antenna. To simplify the transformations we shall assume that the regions are so selected, that their selenographic longitudes φ_1 and φ_2 coincide, while the latitudes are equal in their absolute values : $|\psi_1| = |\psi_2| = \psi$. We shall further admit that the values of the parameters δ, ξ and T of the corresponding regions may be represented in the form

$$\delta_1 = \delta + \Delta\delta, \quad \delta_2 = \delta - \Delta\delta, \quad \xi_1 = \xi + \Delta\xi, \quad \xi_2 = \xi - \Delta\xi.$$
$$T_{H_1} = T_H + \Delta T_H, \quad T_{H_2} = T_H - \Delta T_H, \qquad (2)$$

where δ, ξ and T_H are the values of the respective quantities for a uniform model of the Moon, while the deflections from these values $\Delta\delta, \Delta\xi$ and ΔT_H are small. Moreover, in correspondence with the results of computations of reference work [9], we admit, that T , i.e.the temperature of the subsolar point in regions 1 and 2 is identical.

Let us introduce the denotations

$$\begin{aligned} &\Phi = \Phi_0 - \xi, \qquad \Phi_0 = \Omega t - \varphi \\ &1 + 2\delta\cos r' + 2\delta^2\cos^2 r' = f(\delta), \\ &\cos r'(1 + 2\delta\cos r')/f(\delta) = g(\delta). \end{aligned} \qquad (3)$$

Taking into account that for small $\Delta\xi$ the value

$$\cos(\Phi \pm \Delta\xi) = \cos\Phi \mp \sin\Phi\Delta\xi,$$

and also rejecting the terms containing the products of small quantities $\Delta T_H, \Delta\delta$ and $\Delta\xi$, we shall obtain from (1)

$$T_{H_1} - T_{H_2} = 2(1-R)\Big[\Delta T_H\Big\{1 - \frac{a_0}{2}\eta(\psi) + a_1\eta(\psi)\frac{\cos\Phi}{\sqrt{f(\delta)}}\Big\} -$$
$$- a_1 D\eta(\psi)\frac{\sin\Phi\Delta\xi - g(\delta)\cos\Phi\Delta\delta}{\sqrt{f(\delta)}}\Big],$$
$$T_{H_1} + T_{H_2} \doteq 2(1-R)\Big[T_H + D\eta(\psi)\Big(\frac{a_0}{2} - \frac{a_1\cos\Phi}{\sqrt{f(\delta)}}\Big)\Big]. \qquad (4)$$

Hence

$$F(\Phi)=\frac{T_{я_1}-T_{я_2}}{T_{я_1}+T_{я_2}}=\Delta T_н\frac{1-\eta(\psi)\left(\frac{a_0}{2}-\frac{a_1\cos\Phi}{\sqrt{f(\delta)}}\right)}{T_н+D\eta(\psi)\left(\frac{a_0}{2}-\frac{a_1\cos\Phi}{\sqrt{f(\delta)}}\right)}+$$
$$+\frac{\frac{a_1D\eta(\psi)}{\sqrt{f(\delta)}}(\sin\Phi\Delta\xi-g(\delta)\cos\Phi\Delta\delta)}{T_н+D\eta(\psi)\left(\frac{a_0}{2}-\frac{a_1\cos\Phi}{\sqrt{f(\delta)}}\right)}. \qquad (5)$$

Therefore, the relative difference of brightness temperatures of comparable regions may be represented in the form of linear combination of small differences of night temperature $T_н$, of phase ξ and parameter δ shift, while the coefficients in (5) will be the quantities, determined by the mean values of the corresponding parameters. Note, that because of the presence of coefficients depending on the mean radiophase Φ, the relative difference of brightness temperatures will not remain constant during the lunation, but will be the sum of periodical functions of the mean phase Φ :

$$F(\Phi)=\frac{a+b\cos\Phi}{c+d\cos\Phi}\Delta T_н+\frac{e\sin\Phi}{c+d\cos\Phi}\Delta\xi+\frac{h\cos\Phi}{c+d\cos\Phi}\Delta\delta. \qquad (6)$$

We shall seek the first three Fourier coefficients of this function :

$$\bar F_0=\frac{1}{\pi}\int_{-\pi}^{+\pi}F(\Phi)\,d\Phi;\ \bar F_1=\frac{1}{2\pi}\int_{-\pi}^{+\pi}F(\Phi)\cos\Phi\,d\Phi;\ \bar F_2=\frac{1}{2\pi}\int_{-\pi}^{+\pi}F(\Phi)\sin\Phi\,d\Phi. \qquad (7)$$

It is evident that all these coefficients are a linear combination of the quantities $\Delta T_н$, $\Delta\xi$ and $\Delta\delta$.

The set of values $F(\Phi_i)$, obtained as a result of observations during one or several lunations ar phases Φ_i, can be approximated by a certain periodical function, for example :

$$G(\Phi)=A+B\cos\Phi+C\sin\Phi, \qquad (8)$$

the parameters A, B, C of which may be found by the method of least squares.

Comparison of the computations parameters $\bar{F}_0, \bar{F}_1$ and $\bar{F}_2$, obtained from data on mean characteristics of lunar material, with the corresponding parameters A, B, C, obtained as a result of relative observations of radio-contrasts, provides a system of linear equations, the solution of which allowing to find the differences $\Delta T_н$, $\Delta\xi$ and $\Delta\delta$. searched for. Comparison of the value $\Delta\xi$, obtained by the indicated method, with the values, stemming from the dependence of ε on S, obtained in a one-layer model (1), may serve as an independent criterion of applicability of the model utilized.

Let us consider now the means of passing to brightness temperatures of interest to us, from directly measurable antenna temperatures of comparable regions. The latter may be written in the form:

$$T_{a_{1,2}} = T_{я_{1,2}}(1-\beta_{гл}) + T_я\beta_л = k\alpha_{1,2}.$$

Here $\bar{T}_я$ is brightness temperature of the Moon, averaged by the visible disk; $1-\beta_{гл}$ and $\beta_л$ are the scattering coefficients of the radiotelescope antenna in solid angles beyond the main lobe and within the limits of the lunar disk respectively; $\alpha_{1,2}$ are the accretions of the readings of radiometer's output device, corrected for absorption in the atmosphere, when bringing the antenna on the investigated regions; the coefficient k is the conversion multiplier depending on apparatus parameters. It is assumed that k does not vary during the time of a single session.

It may be shown that

$$F(\Phi) = \frac{T_{я_1} - T_{я_2}}{T_{я_1} + T_{я_2}} = \frac{\alpha_1 - \alpha_2}{\alpha_1 + \alpha_2}\left[1 + \frac{\bar{T}_я\beta_л}{T_я(1-\beta_{гл})}\right], \qquad (10)$$

where $T_я = \frac{1}{2}(T_{я_1} + T_{я_2})$ and $\bar{T}_я$ may be computed for any Φ and operating wavelength λ [9].

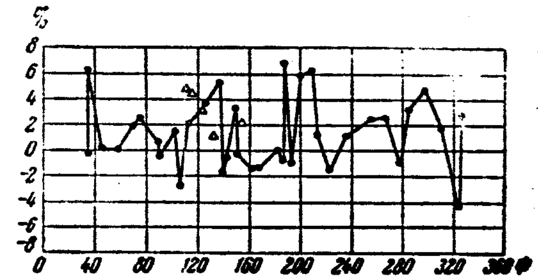
Admitting $\beta_{гл}$ and $\beta_л$ remaining invariable during the measurement cycle, we may determine from the results of measurement of antenna temperature the relative variations of brightness temperatures of comparable regions, and then, using the above-described method, determine the variations $\Delta T_н$, $\Delta\xi$ and $\Delta\delta$ searched for.

3. — RESULTS OF MEASUREMENTS IN 8 MM WAVELENGTH

The first attempts to detect brightness differences in radio emissions of separate regions of the lunar disk were undertaken by us concurrently with A. G. Kislyakov [12] in 1961, in the 8 mm and 4 mm waves. Observations by method of passings of two symmetric regions relative to latitude — "maria" and "continental" — were conducted near the radioquadratures, that is at phases $|\Phi| \simeq \pi/2$. A small excess in brightness temperature of the "maria" region by comparison with the "continental", constituting $(8 \pm 1.5)^{\circ}$ K, was observed in both wavelengths.

The investigations in 8 mm waves were pursued in 1963, with the method being improved. Two regions were selected: they were situated at closer longitudes and latitudes, and equal in magnitude . One of them, was continental ($\varphi = +22^{\circ}$, $\psi = -22^{\circ}$) in the region of the Sacrobosco crater, and the other one — "maria" ($\varphi = 18^{\circ}$, $\psi = 22^{\circ}$) in the region of Mare Serenitatis. At time of observations, computations were conducted with the aid of a special plotting board of optical guide sight installations, assuring the alternate overlapping of the electrical axis of the radiotelescope with each of the regions studied. The correction for the libration was taken into account. The observer followed the visible limb of the lunar disk, retaining it at the reticule, each time placed into the calculated position. First of all alignment took place of electrical axis along Jupiter emission. Then alternate recordings of emission from comparable regions took place, alongside with that of the atmosphere at Moon's height. To control the constance of amplification in the course of a session, calibration signals were used, which were fed from a gas discharge noise generator. The relative difference in brightness temperatures , that is $(T_{м} - T_{к}) / (T_{м} + T_{к})$ was then obtained from formula (10), in which — α_1 and α_2 were obtained by graphical averaging of recordings, conducted during time intervals equal to $(20 \div 30)\tau$, where τ is the time constant of the output filter of the radiometer, and the quantities T and $\overline{T}$ for the phase Φ, corresponding to observation time, were taken according to [9].

The values of the scattering coefficients were obtained by the method of measurements in the nearer zone [11] and for the period of measurements they constituted : $\beta_{гл} = 0.57$ and $\beta_{л} = 0.33$. The measurements were conducted in the course of 25 days of June, July and August 1963. Complementary measurements were conducted in February and March 1964. These results are plotted in Fig. 1.



1. $(T_{я\,мор} - T_{я\,мат}) / (T_{я\,мор} + T_{я\,мат})$

In order to draw conclusions on the presence or absence of differences in the physical parameters of comparable regions, the expression (5) was concretized for the conditions of measurements*. According to [2] the following was admitted :

$$\varepsilon = 1.5, \quad \delta = 2, \quad \xi = 33°, \quad T_п = 407° K, \quad T_н = 125° K, \quad \eta(\psi) = \sqrt{\cos\psi}.$$

For φ and ψ of the investigated regions $\cos r' = 0.916$. Substituting the numerical of the mean values, and replacing $\Delta\xi$ by its expression through $\Delta\delta$ we shall obtain :

$$F(\Phi) = \frac{0.634 + 0.16\cos\Phi}{228 - 46\cos\Phi}\Delta T_н + \frac{0.375\cos\Phi - 0.008\sin\Phi}{5 - \cos\Phi}\Delta\delta - \frac{\sin\Phi}{5 - \cos\Phi}\Delta\xi_л \qquad (11)$$

Inasmuch as $\Delta\xi_л = 2°$, the last term attains 0.8 %.

In correspondence with method described in paragraph 2, the conjunction of measured values of $F(\Phi_i)$ should be approximated by a function of the type (8) and further, comparing the coefficients of the function (8) with the Fourier coefficients of $F(\Phi)$, we would obtain the differences ΔT and $\Delta\delta$ searched for.

Upon substitution in the expression for the coefficients of the Fourier function $F(\Phi)$ of the numerical values, the corresponding equations, according to (11), will take the form

$$\begin{aligned} 3\cdot 10^{-3}\Delta T_н + 7\cdot 10^{-3}\Delta\delta &= A, \\ 1.3\cdot 10^{-3}\Delta T_п + 7\cdot 10^{-2}\Delta\delta &= B, \\ -1.6\cdot 10^{-2}\Delta\delta - 7\cdot 10^{-3} \quad &= C. \end{aligned} \qquad (12)$$

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* In (5), the correction for Sun's latitude difference for the comparable regions is not taken into account. However, for the indicated period of observations it did not exceed 1.6°, which leads to relative variations of brightness temperatures not exceeding 0.3%. The difference in longitude would lead to additional shift of phases by $\Delta\xi_л = 2° = 3.5\cdot 10^{-2}$ rad.

The processing of results by the method of least squares (see Fig. 1) has shown that the mean value of the coefficient A would be $A = (+1.5 \pm 0.5 \cdot 10^{-2})$, that is, the brightness temperature of the "maria" region would be in all 1.5% higher than in the "continental" region as an average for a lunation period.

So far, the measurement precision allowed to provide only an estimate of the amplitude of function's $F(\Phi)$ harmonic term. The approximation of coincidence of the results of measurements leads to the correlation $\sqrt{B^2+C^2} < 3\cdot 10^{-2}$. Utilizing the first equation (12), we have

$$\Delta T_H = 5.0 - 2.3\,\Delta\delta.$$

The substitution of (1?) into the second equation (12) leads to the inequality :

$$[42(\Delta\delta + 0.1)^2 + 2.9(\Delta\delta + 0.4)^2]\,10^{-4} = B^2 + C^2 < 9\cdot 10^{-4}, \qquad (13)$$

whence $(\Delta\delta + 0.12)^2 < 0.21$ or $-0.58 < \Delta\delta < 0.34$. Correspondingly, we have $4.2^\circ < \Delta T_H < 6.4^\circ$. Therefore, the temperature difference on the surface of comparable regions is found to be within the limits $8 \div 13^\circ$, with the "maria" region being hotter than the "continental". Comparison of these values with the results of measurements in the infrared [13, 14] provides the basis to accept the value $\Delta T_H = 4.2 \pm 2^\circ$ as more reliable. The corresponding value is $\Delta\delta \simeq +0.34$. Thus, the parameters of comparable regions differ by no more than 0.7 and at average value $\delta = 2$, they constitute $\delta_1 = 2.35$ for the "maria" region and $\delta_2 = 1.65$ for the "continental" region, with the precision of determination of $\Delta\delta$ for a given ΔT_H being ± 0.05. According to theory [7], a conclusion may be derived therefrom, that the "continental" region is possibly somewhat more "porous" than the "maria".

Therefore the observations are evidence of comparatively small difference in the parameters δ , and also in night temperatures at surfaces of comparable regions, which points to the relative uniformity of the material constituing the upper mantle. If the latter is to be ascribed to differences in the properties of the material abuting to surface, then, assuming $\Delta T_H = 4^\circ$, we obtain $T_{H_1} = 129^\circ K$ and $T_{H_2} = 121^\circ K$. Utilizing the results of calculations of ref. [9], we obtain the values of the parameter for the material of corresponding regions (at the average value $\gamma = 400$): $\gamma_1 \simeq 350$, $\gamma_2 \simeq 450$, that is, the relative parameter differences are near 25%. It is necessary to note that the results of measurements, conducted by us in the 8 mm wave, refer to the layer situated above the surface at the depth near 15 cm.

The conclusion on the relatively small difference in the parameter γ of "maria" and "continental" regions was also recently obtained by M. N. Markov and V. D. Khokhlova [13]. Such a result was obtained according to data of infrared emission flux measurements of the dark surface of the Moon. It was also shown in [13] that the albedo of "maria" and "continental" regions in the $8 - 13\,\mu$ band, probably differ little from one another. That is why the Sinton assumption [14], estimating that the observed discrepancies in brightness temperatures of the infrared emission of the indicated regions are linked with the difference in the albedo, are not corroborated, as is now seen.

Comparison of our data with those of infrared measurements [13] points to the fact, that the difference in the material's properties does not vary very much with depth, at least in a layer of 25 cm thickness.

Therefore, the first results of comparative investigations of the microwave emission of "maria" and "continental" regions with the aid of a radiotelescope of high resolving power point to a probable analogy of the upper mantle of these regions. Such conclusion corroborates the validity of considering the superficial layer of the Moon as quasi uniform along the surface. Subsequent measurements, in particular those in wavelengths near 2 cm, will allow to determine more accurately the degree of inhomogeneity of the surface layer.

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**** THE END ****

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